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Constraining relativistic protons and magnetic fields in galaxy clusters through radio & γ-ray observations : the case of A2256 *(Research Note)*

Gianfranco Brunetti[1,⋆]

INAF - Istituto di Radioastronomia, via P. Gobetti 101,I-40129 Bologna, Italy

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ABSTRACT

Giant radio halos are the most relevant examples of diffuse synchrotron emission from galaxy clusters. A number of these sources have very steep spectrum, with spectral index $\alpha \geq 1.5-1.6$ ($F(\nu) \propto \nu^{-\alpha}$), and are ideal targets to test current models for the origin of the relativistic particles. A2256 hosts the nearest radio halo with very steep spectrum, with $\alpha = 1.61$, and a very large population of relativistic protons in the cluster would be necessary to explain the halo as due to synchrotron emission from secondary particles. In this case the 0.1-1 GeV γ–ray luminosity is expected 10-20 times larger than that of clusters hosting radio halos with similar radio power at GHz frequencies but with spectra more typical of the presently observed halo population, $\alpha \sim 1.2$. Under these assumptions incoming FERMI/GLAST observations are expected to detect A2256, provided that the magnetic field in the central cluster region is $\leq$10-15 μG. We show that this will allow for a prompt test of hadronic models for the origin of radio halos, and for complementary constraints on both the cluster magnetic field and the physics of particle acceleration mechanisms.

Key words. Radiation mechanism: non–thermal - galaxies: clusters: general - radio continuum: general Gamma rays: theory

1. Introduction

Galaxy clusters are the largest gravitationally bound objects in the Universe. During cluster mergers energy may be channelled into the amplification of the magnetic fields (Dolag et al. 2005; Ryu et al. 2008) and into the acceleration of relativistic primary electrons (CRe) and protons (CRp) via shocks and turbulence (*e.g.*, Ensslin et al.1998; Sarazin 1999; Blasi 2001; Ryu et al. 2003; Gabici & Blasi 2003; Pfrommer et al. 2006; Brunetti & Lazarian 2007). CRp have long life-times and remain confined within clusters for a Hubble time (Völk et al. 1996; Berezinsky et al. 1997; Ensslin et al. 1997), they are expected to be the dominant non-thermal particle component in the ICM and should produce secondary particles due to collisions with thermal protons (*e.g.*, Blasi et al. 2007 for review).

Direct evidence for magnetic fields and relativistic particles, mixed with the thermal Intra-Cluster-Medium (ICM), comes from radio observations that detect Mpc-sized diffuse radio sources, radio halos and relics, in a fraction of X-ray luminous galaxy clusters in merging phase (*e.g.*, Ferrari et al. 2008 for review). Extended and fairly regular diffuse synchrotron emission, in the form of giant radio halos, may be produced by secondary electrons injected during proton-proton collisions (hadronic models, e.g. Dennison 1980; Blasi & Colafrancesco 1999; Pfrommer & Ensslin 2004), or assuming that relativistic electrons are re-accelerated in-situ by MHD turbulence generated in the ICM during cluster-cluster mergers (re-acceleration models, e.g. Brunetti et al. 2001, 2004; Petrosian 2001; Fujita et al. 2003; Cassano & Brunetti 2005). Unavoidable γ-ray emission, due to the decay of the neutral pions generated through proton-proton collisions, is expected in the context of hadronic models (e.g. Blasi & Colafrancesco 1999; Miniati 2003; Pfrommer & Ensslin 2004). Some γ-ray emission is also expected from those re-acceleration models that account for the general situation where both relativistic protons and electrons (including secondaries) interact with MHD turbulence (Brunetti & Blasi 2005; Brunetti 2008). Those halos with very steep spectrum are suitable targets to constrain models and favour a turbulent re-acceleration scenario (*e.g.*, Brunetti et al. 2008): in fact it must be admitted that clusters hosting radio halos with very-steep spectrum should contain a very large population of CRp assuming the hadronic scenario; this also implies an unavoidably large γ-ray emission from these clusters.

Only upper limits to the γ-ray emission from clusters have been obtained so far (Reimer et al. 2003; Aharonian et al. 2009b), implying in some cases a fairly stringent constraint to the energy density of CRp, <10 % of that of the thermal ICM (Aharonian et al. 2009a). The FERMI/GLAST telescope will shortly provide more stringent constraints to the γ-ray properties of clusters and to the energy density of CRp.

The radio halo in A2256 is the nearest steep-spectrum halo, and we show that the incoming FERMI/GLAST data will provide a prompt test of the hadronic scenario and allow for constraining the cluster-magnetic field.

A ΛCDM cosmology ($H_o = 70\,\mathrm{km\,s^{-1}\,Mpc^{-1}}$, $\Omega_m = 0.3$, $\Omega_\Lambda = 0.7$) is adopted.

2. The cluster Abell 2256

Abell 2256 is a massive galaxy cluster at z=0.058, with 0.1–2.4 keV X-ray luminosity $L_X \simeq 3.8 \cdot 10^{44}$erg/s (*e.g.*, Ebeling et al. 1996). The dynamical state of A2256 is complex and is thought to consist of at least three merging systems based on optical velocity dispersion (Berrington et al. 2002; Miller et al.

Send offprint requests to: G. Brunetti
⋆ e-mail: brunetti@ira.inaf.it

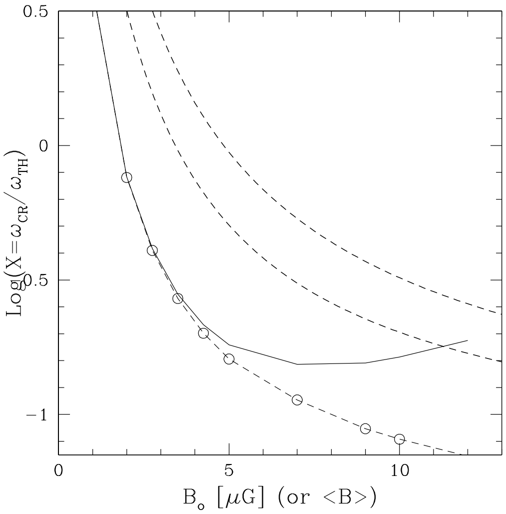

Fig. 1. Ratio between relativistic CRp and thermal energy densities (for $r \leq 1.5 r_c$) for the *Steep* (dashed line, open circles) and *Flat* models (red dashed lines) as a function of $< B >$ (*Steep* model) and B_o (*Flat* model; b=0.5,1 from bottom to top). The ratio between CRp+B and thermal energy densities is shown for the *Steep* model (solid line).

2003). A complex dynamics is also suggested by X–ray observations that revealed two separate peaks in the X-ray surface brightness distribution corresponding to the primary cluster and to the secondary subcluster, that is infalling onto the primary from the north–east (Briel et al. 1991; Sun et al. 2002).
Radio observations revealed complex diffuse emission on large scale (Bridle et al. 1979; Rottgering et al. 1994; Clarke & Ensslin 2006; Brentjens 2008) that consists of a bright relic, north–west of the cluster center, and of a fainter steep-spectrum Mpc–scale radio halo in the cluster central region. Deep observations at 1400 and 300 MHz detect diffuse radio-halo emission up to a distance from cluster center $\sim 1.5\, r_c \approx 520$ kpc (Clarke & Ensslin 2006; Brentjens 2008). A detailed spectral analysis of the halo emission derived a integrated spectral index between 0.3–1.4 GHz, $\alpha = 1.61$ ($F(\nu) \propto \nu^{-\alpha}$), once the contribution from the embedded discrete radio sources is subtracted (Brentjens 2008).

3. Hadronic models: formalism

The decay chain that we consider for the injection of secondary particles in the ICM due to p-p collisions is (Blasi & Colafrancesco 1999):

$$p + p \rightarrow \pi^0 + \pi^+ + \pi^- + \text{anything}$$
$$\pi^0 \rightarrow \gamma\gamma$$
$$\pi^\pm \rightarrow \mu + \nu_\mu \quad \mu^\pm \rightarrow e^\pm \nu_\mu \nu_e .$$

that is a threshold reaction that requires protons with kinetic energy larger than $T_p \approx 300$ MeV.
The injection rate of pions is :

$$Q_\pi^{\pm,o}(E_{\pi^{\pm,o}}, t) = n_{th} c \int_{p_*} dp N_p(p,t) \beta_p \frac{F_\pi(E_\pi, E_p)\sigma^{\pm,o}(p)}{\sqrt{1+(m_p c/p)^2}}, \qquad (1)$$

where n_{th} is the number density of thermal protons, and F_π is the spectrum of pions from the collision between a CRp of energy E_p and thermal protons (taken from Brunetti & Blasi 2005). The inclusive cross section, $\sigma(p)$, is taken from the fitting formulae in Dermer (1986b) which allow to describe separately the rates of generation of π^-, π^+ and π^o, and $p_* = \max\{p_{_{tr}}, p_\pi\}$; p_{tr} is the threshold momentum of protons.
The spectrum of γ-rays produced by the decay of the secondary π^o is (*e.g.,* Dermer 1986ab; Blasi & Colafrancesco 1999):

$$Q_\gamma(E_\gamma) = 2 \int_{E_{min}}^{E_p^{max}} \frac{Q_{\pi^o}(E_{\pi^o})}{\sqrt{E_\pi^2 - m_\pi^2 c^4}} dE_\pi \qquad (2)$$

where $E_{min} = E_\gamma + 1/4 m_\pi^2 c^4 / E_\gamma$.

Charged pions decay into muons and secondary pairs (electrons and positrons). Under the assumption that secondaries are not accelerated by other mechanisms, their spectrum approaches a stationary distribution due to the competition between injection and energy losses (*e.g.,* Dolag & Ensslin 2000) :

$$N_e^\pm(p) = \frac{1}{\left|\left(\frac{dp}{dt}\right)_{\rm loss}\right|} \int_p^{p_{\rm max}} Q_e^\pm(p) dp. \qquad (3)$$

where $Q_e^\pm$ is the injection rate of secondaries (e.g. Blasi & Colafrancesco 1999; Moskalenko & Strong 1998), and radiative losses, that dominate for $\gamma > 10^3$ electrons in the ICM, are (*e.g.,* Sarazin 1999):

$$\left|\left(\frac{dp}{dt}\right)_{\rm loss}\right| \simeq 3.3 \times 10^{-32} \Big(\frac{p/m_e c}{300}\Big)^2 \left[\left(\frac{B_{\mu G}}{3.2}\right)^2 + (1+z)^4\right] \qquad (4)$$

Assuming a power law distribution of CRp, $N_p(p) = K_p p^{-s}$, the spectrum of secondaries at high energies, $\gamma > 10^3$, is $N_e(p) \propto p^{-(s+1)}\mathcal{F}(p)$; $\mathcal{F}$ accounts for the Log–scaling of the p-p cross section at high energies and makes the spectral shape slightly flatter than $p^{-(s+1)}$ (*e.g.,* Brunetti & Blasi 2005). The synchrotron spectrum from secondary e$^\pm$ is (e.g. Ribicky & Lightman 1979):

$$J_{syn}(\nu) = \sqrt{3}\frac{e^3}{m_e c^2} B \int_0^{\pi/2} d\theta sin^2\theta \int dp N_e(p) F\Big(\frac{\nu}{\nu_c}\Big)$$
$$\simeq C(\alpha, T) X n_{th}^2 \frac{B^{1+\alpha}}{B^2 + B_{cmb}^2} \nu^{-\alpha} \qquad (5)$$

where C is a constant, $X = \omega_{CR}/\omega_{TH}$ is the ratio between the energy densities of CRp and thermal protons, F is the synchrotron Kernel, ν_c is the critical frequency; $\alpha \simeq s/2 - \Delta$, $\Delta \sim 0.1 - 0.15$ due to the Log-scaling of the cross section.

4. Results

In this Section we show that the steep spectrum of the halo in A2256 (Sect.2) allows for a prompt test of hadronic models and to constrain the magnetic field in the ICM.
We assume that the radio halo is due to synchrotron emission from scondary electrons, in which case the observed synchrotron spectral index, $\alpha = 1.61$, implies $s = 3.4$–3.5. Parameters for the thermal ICM distribution in A2256, n_o, T, r_c, and β, are derived from Henry et al. (1993) and Myers et al. (1997).
We first adopt a *Steep* model that assumes a constant ratio between the CRp and energy density of thermal protons, $\omega_{CR}/\omega_{TH} = X$, and model the halo region with a homogeneus sphere with radius $R_H \sim 1.5 r_c$ and a volume averaged field (weighted for the synchrotron emissivity) $< B >$. The value of

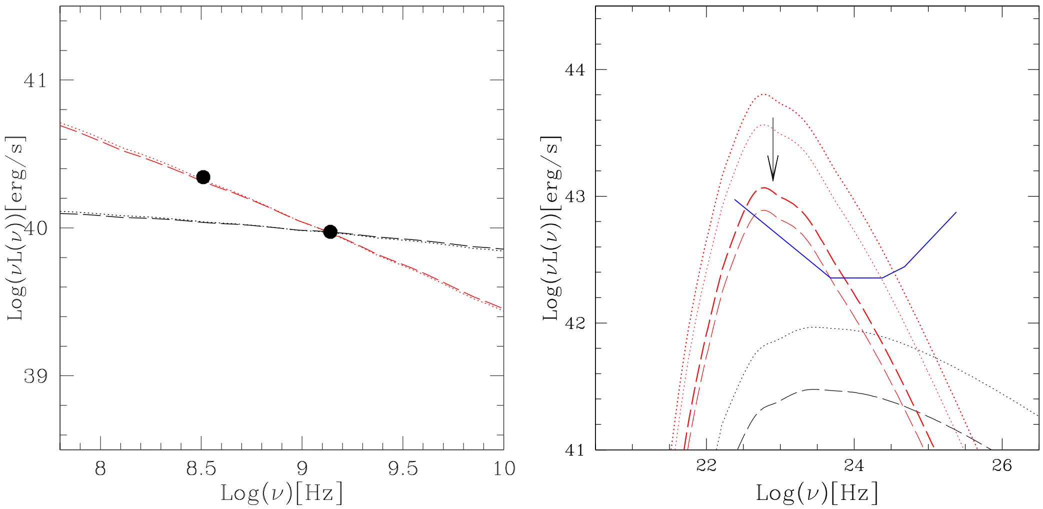

Fig. 2. Radio (left) and (π^o–decay) γ–rays from $r \leq 3r_c$ (right) from A2256 assuming b=0.5 and B_o=2.65 (dotted lines) and 10 μG (dashed lines). Calculations are shown for $s = 3.5$ (red lines) in the case of the *Flat* (thick lines) and *Steep* model (thin lines). Results for a *Steep* model with $s = 2.4$ are also shown for comparison. Monochromatic radio luminosities at 330 and 1400 MHz (filled points), the EGRET upper limit (arrow) and the FERMI/GLAST reference sensitivity (solid–blue line) are also shown.

X, considering relativistic CRp only, that is requested to match the observed synchrotron spectrum is shown in Figure 1 as a function of $< B >$. We find that $< B > \leq 2\mu$G can be excluded since the CRp energy density becomes larger than the cluster thermal budget. For stronger magnetic fields, $< B > \geq 4 - 5\mu$G, $\omega_{CR} \leq 0.2\omega_{TH}$ and the non-thermal component becomes magnetically dominated. The non-thermal energy content reaches a minimum, $\sim 0.16\omega_{TH}$, for $< B > \approx 7 - 9\mu$G that marks the minimum energy condition for hadronic models (Pfrommer & Ensslin 2004). If we do not restrict to relativistic CRp and include also sub-relativistic CRp, due to the very steep spectrum, the required energy budget is much larger than that in Figure 1, $\omega_{CR} \propto p_{min}^{-s+3}$, making the energetics of CRp considerably larger.

We assume a spatial profile of the magnetic field $B = B_o \left(\frac{n_{th}}{n_o}\right)^b$ (*e.g.*, Govoni & Feretti 2004) and find that the *Steep* model produces a radio-halo brightness profile that drops by a factor 25–40 at $r \sim 1.5\, r_c$, by adopting b=0.5–1 and $B_o \geq 5\mu$G. This is not consistent with the observed profile that drops, at the same distance, by only a factor 5–8 (Clarke & Ensslin 2006; Brentjens 2008). Thus we consider a *Flat* hadronic model, with ω_{CR}=const up to $r \sim 1.5\, r_c$ and X=const for larger r, that produces a drop of the brightness of a factor 8–12 at $r \sim 1.5\, r_c$ for the range of (b, B_o) given above; this is our *reference* model. The energy request of the *Flat* hadronic model is also reported in Figure 1 considering the conservative case of relativistic CRp only. The large energy budget for the non-thermal components is a drawback of an hadronic origin of the radio halo in A2256.

This large budget and the steep spectrum of CRp imply an unavoidably efficient production of γ–rays at 0.1–1 GeV due to π^o decay. Consequently FERMI/GLAST observations provide an efficient and complementary way to test a hadronic origin of the halo.

In Figure 2 we show the expected radio (left) and γ-ray (right) spectra of A2256 for different values of B_o (see caption) (models anchored to the observed 1.4 GHz emission); we also report the case of a hadronic model with $s = 2.4$.

We find that assuming a hadronic origin of the radio halo and adopting the appropriate spectrum of CRp, the γ–ray upper limit obtained with EGRET observations (Reimer et al. 2003) already constrains $B_o > 2.5\mu$G. Most important FERMI/GLAST should be able to detect Abell 2256 in the next years, provided that $B_o \leq 10 - 15\mu$G. This is highlighted in Figure 3 where we show the expected photon number with $E_\gamma \geq 100$ MeV as a function of B_o in the case of both *Steep* and *Flat* hadronic models.

5. Discussion and Conclusions

Radio halos have typical synchrotron spectral indices $\alpha \sim 1.2 - 1.3$ (*e.g.*, Ferrari et al. 2008), yet halos with steeper spectrum might be more common in the Universe (*e.g.*, Cassano et al. 2006) and present observations at GHz frequencies may select preferentially those halos with flatter spectrum. The discovery of a few radio halos with spectral index $\alpha > 1.5 - 1.6$ suggests that the emitting electrons are accelerated by rather inefficient mechanisms, *e.g.*, turbulent acceleration, and constrains models, such as the hadronic one, that would require very large energy budget to explain these sources (*e.g.*, Brunetti et al.2008).

A2256 hosts the nearest radio halo with steep spectrum, $\alpha = 1.61$, that would request a spectral slope of CRp $s = 3.4 - 3.5$ adopting the hadronic scenario; in this case only a small fraction of the total energy-budget of supra-thermal CRp is expected to be associated with relativistic CRp. We exploit two approaches based on hadronic models : a *Steep* model that assumes a constant fraction $X = \omega_{CR}/\omega_{TH}$ and a *Flat* model that assumes ω_{CR}=const in the halo volume and X=const outside. The last one is our *reference* model since the observed halo–brightness profile of A2256 in fact implies a rather flat spatial distribution of CRp.

Even by considering only relativistic CRp, the hadronic model requires a large CRp-energy budget to explain the halo in A2256 for central fields $B_o < 10\mu$G. This is a drawback of the hadronic scenario and also implies that the expected γ–ray luminosity of A2256 would be 10-20 times that of similar clusters hosting halos with the same radio luminosity but with $\alpha \sim 1.2$. Under these conditions we show that FERMI/GLAST should be able to detect A2256.

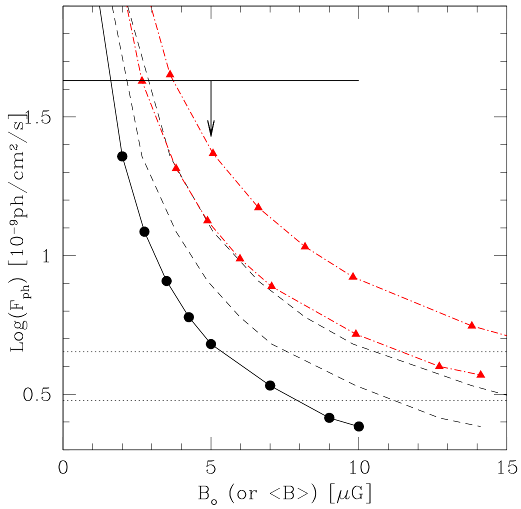

Fig. 3. Photon fluxes for $>$ 100 MeV are shown as a function of B_o assuming *Flat* (red dot-dashed lines) and *Steep* models (dashed lines) with b=0.5 and 1 (bottom to top). Photon flux vs $< B >$ for the *Steep* model is also shown (solid line with points). EGRET upper limit (arrow) and FERMI/GLAST sensitivity-range (dotted lines) are shown.

Non detection would imply either that the halo is not of hadronic origin, or that the magnetic field in the central cluster region is $B_o \geq 10-15\mu$G. In the latter case however we would admit the ad hoc possibility that A2256 is a cluster with unusually strong magnetic field since strong fields are presently observed only in cool-core clusters (*e.g.,* Carilli & Taylor 2002; Govoni & Feretti 2004); future observations of Faraday Rotation will provide complementary information on the cluster-magnetic field.
On the other hand, detection of steep–spectrum γ–ray emission from A2256 would imply a hadronic origin of the halo, allowing also for an unprecedented measure of the magnetic field strength in the cluster. This will also suggest that very unusual acceleration mechanisms operate in the ICM, channeling a large fraction of the cluster energy into CRp with very steep spectrum.
If the halo is generated by turbulent re-acceleration the maximum γ-ray luminosity that is expected from A2256 can be estimated by requiring that the emission from secondaries matches the radio flux at the highest frequencies and is much smaller than that at lower frequencies (assumed to be dominated by re-accelerated electrons) (Reimer et al.2004; Donnert et al. 2009). This gives a γ-ray luminosity similar to that of the model with s = 2.4 in Figure 2 implying that detection would be possible only for weak fields, $B_o < 1\mu$G, with the γ-ray spectrum much flatter than in the case of a hadronic origin of the halo.

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References

Aharonian F.A., et al., 2009a, A&A 495, 27
Aharonian F.A., et al., 2009b, A&A 502, 437
Berezinsky V.S., Blasi P., Ptuskin V.S., 1997, ApJ 487, 529
Berrington R.C., Lugger P.M., Cohn H.N., 2002, AJ 123, 2261
Blasi P., 2001, APh 15, 223
Blasi P., Colafrancesco S., 1999, APh 12, 169
Blasi P., Gabici S., Brunetti G., 2007, Int. J. Mod. Phys. A 22, 681
Brentjens M.A., 2008, A&A 489, 69
Bridle, A.H., Fomalont E.B., Miley G.K., Valentijn E.A., 1979, A&A 80, 201
Briel U.G., et al., A&A 246, L10
Brunetti G., 2008, ArXiv 0810.0692
Brunetti G., Setti G., Feretti L., Giovannini G., 2001, MNRAS 320, 365
Brunetti G., Blasi P., Cassano R., Gabici S., 2004, MNRAS 350, 1174
Brunetti G., Blasi P., 2005, MNRAS 363, 1173
Brunetti G., Lazarian A., MNRAS 378, 245
Brunetti G., et al. 2008, Nature 455, 944
Carilli C.L., Taylor G.B., 2002, ARA&A 40, 319
Cassano R., Brunetti G. 2005, MNRAS 357, 1313
Cassano R., Brunetti G., Setti G., 2006, MNRAS 369,1577
Clarke T.E., Ensslin T.A., 2006, ApJ 131, 2900
Dennison B., 1980, ApJ 239, L93
Dermer C.D., 1986a, A&A 157, 223
Dermer C.D., 1986b, ApJ 307, 47
Dolag K., Ensslin T.A., 2000, A&A 362, 151
Dolag K., Grasso D., Springel V., Tkachev I., 2005, JCAP 1, 9
Donnert J., Dolag K., Brunetti G., Cassano R., Bonafede A., 2009, arXiv:0905.2418
Ebeling H., Voges W., Böhringer H., Edge A.C., Huchra J.P., Briel U.G., 1996, MNRAS 281, 799
Ensslin T.A., Biermann P.L., Kronberg P.P., Wu X.-P., 1997, ApJ 477, 560
Ensslin T.A., Biermann P.L., Klein U., Kohle S., 1998, A&A 332, 395
Ferrari F., Govoni F., Schindler S. et al. 2008, SSRv 134, 93
Fujita Y., Takizawa M., Sarazin C.L., 2003, ApJ 584, 190
Gabici S., Blasi P., 2003, ApJ 583, 695
Govoni F., Feretti L., 2004, Int. J. Mod. Phys. D 13, 1549
Henry J.P., Briel U.G., Nulsen P.E.J., 1993, A&A 271, 413
Miller N.A., Owen F.N., Hill J.M., 2003, AJ 125, 2393
Miniati F., 2003, MNRAS 342, 1009
Moskalenko I.V., Strong A.W., 1998, ApJ 493, 694
Myers S.T., Baker J.E., Readhead A.C.S., Leitch E.M., 1997, ApJ 485, 1
Petrosian V., 2001, ApJ 557, 560
Pfrommer C., Enßlin T. A. 2004, A&A 413, 17
Pfrommer C., Springel V, Enßlin T.A., Jubelgas M., 2006, MNRAS 367, 113
Reimer A., Reimer O., Schlickeiser R., Iyudin A., 2004, A&A 424, 773
Reimer O., Pohl M., Sreekumar P., Mattox J.R., 2003, ApJ 588, 155
Ribicky G.B., Lightmann A.P., *Radiative Processes in Astrophysics*, New York, Wiley-Interscience, 1979
Röttgering H, Snellen I., Miley G., de Jong J.P., Hanisch R.J., Perley R., 1994, ApJ 436, 654
Ryu D., Kang H., Hallman E., Jones T.W., 2003, ApJ 593, 599
Ryu D., Kang H., Cho J., Das S., 2008, Science 320, 909
Sun M., Murray S.S., Markevitch M., Vikhlinin A., 2002, ApJ 565, 867
Völk H.J., Aharonian F.A., Breitschwerdt D., 1996, SSRv 75, 279